THE ACCURACY OF THE ORIFICE IN MEASURING
SMALL FLOWS OF A GAS

by

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In all scientific work the accuracy of the results is dependent on the accuracy of the measurements taken or used. The ideal measuring device in addition to being accurate, should be dependable and simple.

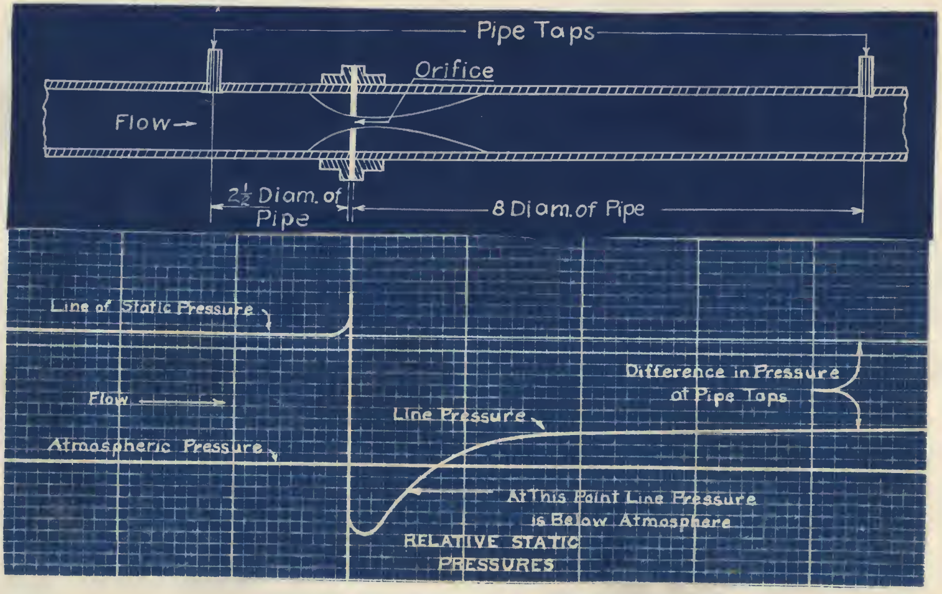
The thin-plate orifice used as a device for measuring small flows of a gas satisfies two of the above mentioned requirements, dependability and simplicity. The object of this research was to determine the accuracy with which a thin-plate orifice could be used to measure the volume or weight of a flowing gas.

First a series of discharge coefficients were determined and a curve was plotted using these values. (See Figure 3 - 7) Taking from the curve the value of a discharge coefficient, this value was used to calculate the amount of flow. From the calculated flow and the observed flow the accuracy was determined.

The thin-plate orifice meter as used consisted of a thin metal plate, with a concentric hole through it, placed between two flanges in a pipe line with the center of the plate in the center of the pipe. The pressure is measured on each side of the plate through holes in the pipe. (See Figure 1) The pipe was of brass .625 inch in diameter. There was about 36 inches of pipe on each side of the orifice plate. The outer end of the pipe was connected to a gas burner. By adjusting the mixing needle the rate of flow and the pressure on the downstream side (low pressure side) of the orifice plate could be regulated.

The gas used in the research was air, which was supplied by a metering tank of the water seal type.

A water manometer was used to measure the upstream or tank pressure above



Pipe Taps
Orifice
Flow
2½ Diam. of Pipe
8 Diam. of Pipe
Line of Static Pressure
Flow
Atmospheric Pressure
Line Pressure
Difference in Pressure of Pipe Taps
At This Point Line Pressure is Below Atmosphere
RELATIVE STATIC PRESSURES

Figure 1

atmosphere and also the pressure difference across the orifice plate. This pressure difference is known as the differential pressure.

There were five different sizes of orifices used in the tests. (See Table 1) With each orifice tests were run with the tank pressure 5.25, 5.00, 4.75, 4.50 and 4.25 inches of water above atmospheric pressure. With each orifice and each tank pressure as given above, tests were run with the differential pressure at 4.0, 3.0, 2.5, 2.0, 1.5, and 1.0 inches of water. Two separate sets of readings were taken at each test set up.

The procedure followed in taking a set of readings was as follows: An orifice plate was fastened in the pipe line. The desired pressure in the tank or upstream pressure above atmosphere was obtained by varying the weights on the top of the tank. Then the desired differential pressure was produced by adjusting the needle valve in the gas burner. The bell or movable section of the metering tank was raised and allowed to remain stationary until the air in the tank was again at room temperature. The outlet valve was opened. Stop watches were used to determine the time necessary for one cubic foot of air to flow through the orifice. The time was recorded. The room temperature, tank temperature, and barometric pressure were also recorded.

The differential pressure was changed and the test repeated. After tests had been run using the six different differential pressures, the tank or upstream pressure was changed. The tests were again run with the six differential pressures. When tests had been run using the five different tank pressures, another orifice was put in the pipe line.

The theory of the orifice is as follows: If a plate with a hole through it is placed in a pipe line, with the hole concentric with the pipe, the flowing gas will follow the same path that it would follow if flowing through a

nozzle.

The top drawing of Figure 2 shows the customary presentation of the flow lines of a gas that is flowing through an orifice; but, in reality, this condition does not exist. The bottom drawing shows the changes that are probably taking place.

The gas in the center of the pipe passes through the orifice with considerable longitudinal acceleration, but without transverse deflection. The gas near the wall of the pipe is deflected radially inward toward the center. Consequently, the gas near the edge of the orifice is moving transversely as well as longitudinally. This causes the gas stream to contract. The point of maximum contraction (the vena contracta) is reached just below the orifice plate. (See Figure 2) At the vena contracta the pressure is lower than on the entrance side of the orifice. After the vena contracta is passed the pressure increases and the stream fills the pipe. The viscous drag of the quiet gas in the "lee" of the orifice slows down the edge of the stream, turning it outward, and causing it to form a recovery "cone".

Figure 1 shows the static pressure distribution along the pipe in the region of the orifice plate. The point of lowest pressure is at the vena contracta. The maximum pressure recovered is less than the upstream pressure.

In American practice three particular arrangements for the location of the taps (holes in the pipe for the purpose of measuring the upstream and downstream pressure) have become more or less standard. They are, flange taps, throat taps and pipe taps. Pipe taps were used to measure the pressures.

If an orifice is to be used to measure a flowing gas, first a series of discharge coefficients (ratio of observed flow to theoretical flow) must be obtained experimentally. To use these discharge coefficients in another setup,

TABLE I

ORIFICE DATA

ORIFICE NO.	THICKNESS OF PLATE Inch	OUTSIDE DIA. Inch	HOLE DIA. Inch	MATERIAL
1	.0375	.9375	.0595	Steel
2	.0375	.9375	.0420	Steel
3	.0375	.9375	.0465	Steel
4	.0375	.9375	.0520	Steel
5	.0375	.9375	.0550	Steel

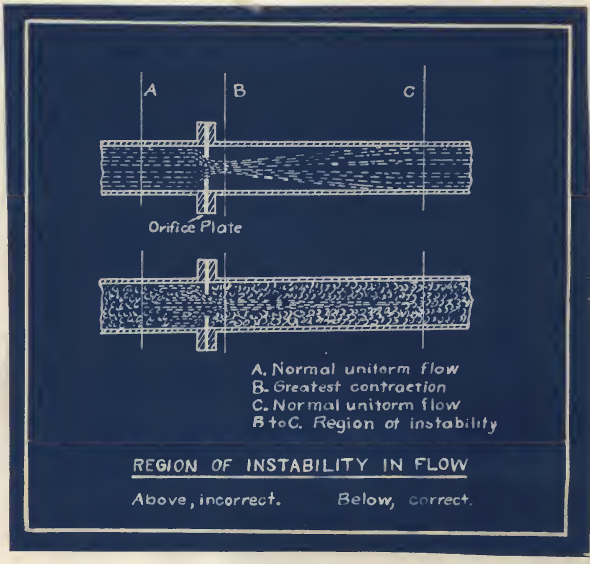


Figure 2

both setups must be identical if accurate results are to be obtained.

The adiabatic, or St. Venant, equation was used to calculate the theoretical rate of flow. This equation is based on the following assumptions. (c) The flow is adiabatic. (b) There is no energy loss between the sections at which the pressures are measured. (c) The stream lines are perpendicular to the cross section. The velocity is uniform throughout the cross section.

As the energy per pound of gas is assumed to be constant, the potential energy liberated between the upstream (suffix 1) point and the plane of the orifice (suffix 2) will be equal to the kinetic energy gained.

$$K_2 - K_1 = (E_1 + P_1\overline{V}_1) - (E_2 + P_2\overline{V}_2)$$

K = kinetic energy $= \frac{V^2}{2g}$

E = internal energy $= \frac{P\overline{V}}{k-1}$

V = velocity of gas in feet per second

g = acceleration due to gravity

$k = C_p/C_v$ = ratio of specific heats

$\overline{V}$ = specific volume in cubic feet per pound

P = pressure in pounds per square foot (abs.)

The final form of the equation is as follows:

$$\Omega = \frac{Q}{A_2 \left[\dfrac{2g \frac{k}{k-1} P_1 V_1 \left(1 - R^{\frac{k-1}{k}}\right) R^{\frac{2}{k}}}{1 - \frac{1}{n^2} R^{\frac{2}{k}}} \right]^{\frac{1}{2}}}$$

Ω = discharge coefficient

Q = discharge in pounds per second

A_2 = area of hole in orifice plate in square feet

g = acceleration due to gravity

k = ratio of the specific heats of gases

P_1 = upstream pressure in pounds per square foot (abs.)

P_2 = downstream pressure in pounds per square foot (abs.)

R = P_2/P_1

W_1 = upstream density in pounds per cubic foot

$n = \dfrac{\text{area of upstream pipe}}{\text{area of hole in orifice plate}}$

The equation just given can be used as long as P_2 is greater than the critical pressure. The critical pressure is that minimum pressure to which an expansive fluid will expand in passage through a convergent channel connecting a higher and a lower pressure region. The flow will increase as P_2 approaches P_c, the critical pressure, and will be a maximum when P_2 equals P_c. As P_2 becomes less than P_c, the weight of flow will remain constant at the maximum value. For air when the flow is a maximum P_2 is approximately .53 of P_1 or P_c = .53 of P_1.

The value for Ω is determined experimentally. The discharge coefficient, Ω, is introduced to allow for the following variations from assumed conditions: The flow is not adiabatic, due to interference of the friction and impact order. The pressure P_2 is measured at the downstream tap instead of at the orifice plate. The area of the hole in the orifice plate is used instead of the area of the vena contracta. The discharge coefficients also corrects for the effects of viscosity, and for deviations from the perfect gas law.

Discharge coefficients were calculated for the five orifices with upstream pressures of [illegible], 4.75, and 4.[illegible] inches of water above atmosphere, and differential pressures of 4.0, 3.0, 2.5, 2.0, 1.5, and 1.0 inches of water. These discharge coefficients were plotted against values of P_2/P_1. (See Figure 3 - 7) A curve was drawn through the points.

In determining the accuracy of the orifice in measuring a flowing gas, the theoretical flow was first calculated using the St. Venant equation. The difference between the theoretical flow and the observed flow was divided by the observed flow. This result multiplied by 100 gave the deviation of the theoretical flow from the observed or actual flow, in per cent of the observed flow. The deviation in per cent subtracted from 100 would give the per cent of accuracy of the orifice in measuring flows.

Accuracies were determined from data for the five orifices with upstream pressures of [illegible].00 and [illegible].50 inches of water above atmosphere, and differential pressures of 4.0, 3.0, 2.5, 2.0, 1.5, and 1.0 inches of water. (See Table 2)

A minimum accuracy of approximately 99.70% is desirable. Some of the accuracies obtained are lower than this. This variation in accuracy was probably due to the unsteadiness of the flow of the air from the source of supply. The movable tank or bell of the metering tank did not drop at a uniform rate, thereby causing the flow to be unsteady.

Another source of error was the collecting of small particles of moisture, dust, etc. on the edge of the hole in the orifice plates. It was necessary to clean the orifice plates after every four to six tests.

It is believed that higher accuracies can be obtained provided a source for supplying air at a steady pressure, or flow, were available. The author believes that, as a whole, the accuracies of the orifices tested were high

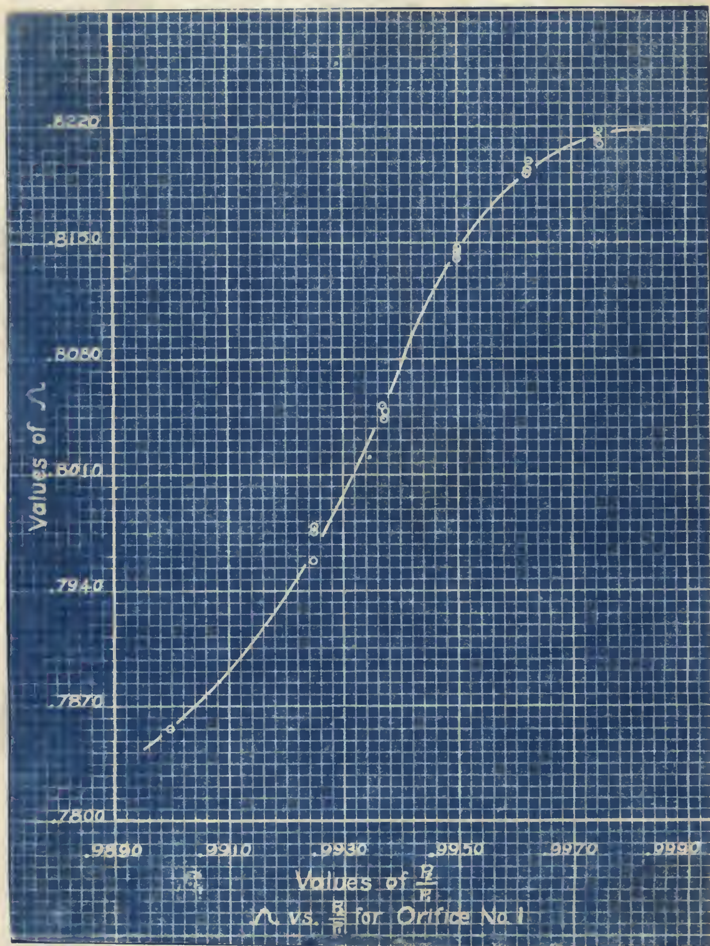

.8220
.8150
.8080
.8010
.7940
.7870
.7800
Values of Λ
.9890
.9910
.9930
.9950
.9970
.9990
Values of $\frac{p}{P}$
Λ vs. $\frac{p}{P}$ for Orifice No. 1

Figure 3

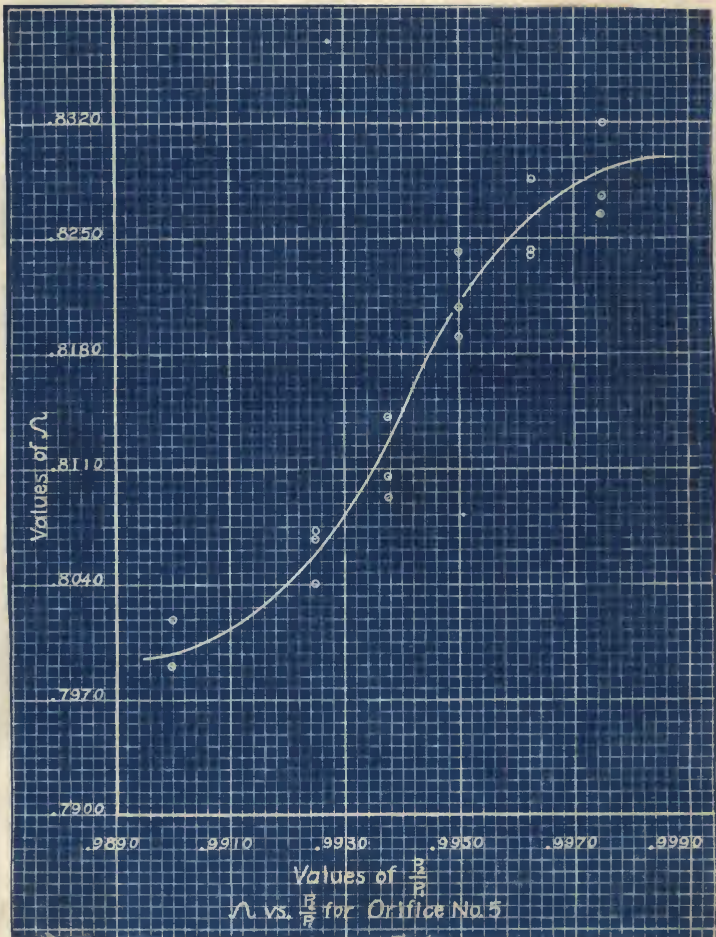

.8320
.8250
.8180
.8110
.8040
.7970
.7900
Values of Ω
.9890
.9910
.9930
.9950
.9970
.9990
Values of $\frac{P_2}{P_1}$
Ω vs. $\frac{P_2}{P_1}$ for Orifice No. 5

Figure 4

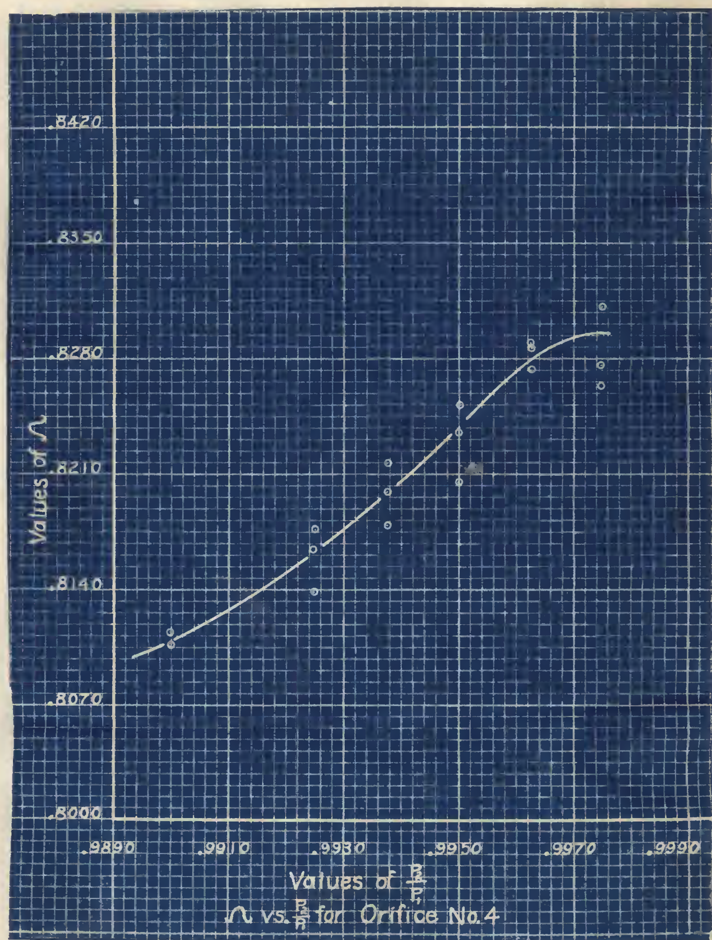

.8420
.8350
.8280
.8210
.8140
.8070
.8000
Values of Λ
.9890
.9910
.9930
.9950
.9970
.9990
Values of $\frac{P_2}{P_1}$
Λ vs. $\frac{P_2}{P_1}$ for Orifice No. 4

Figure 5

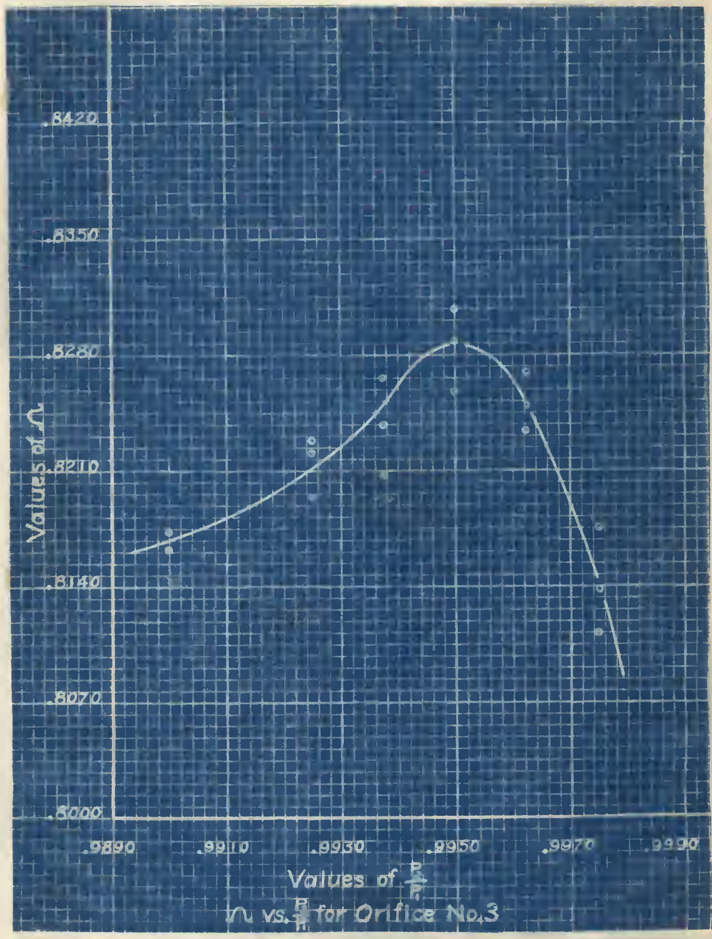

.8420
.8350
.8280
.8210
.8140
.8070
.8000
Values of Ω
.9890
.9910
.9930
.9950
.9970
.9990
Values of $\frac{P_2}{P_1}$
Ω vs. $\frac{P_2}{P_1}$ for Orifice No.3

Figure 6

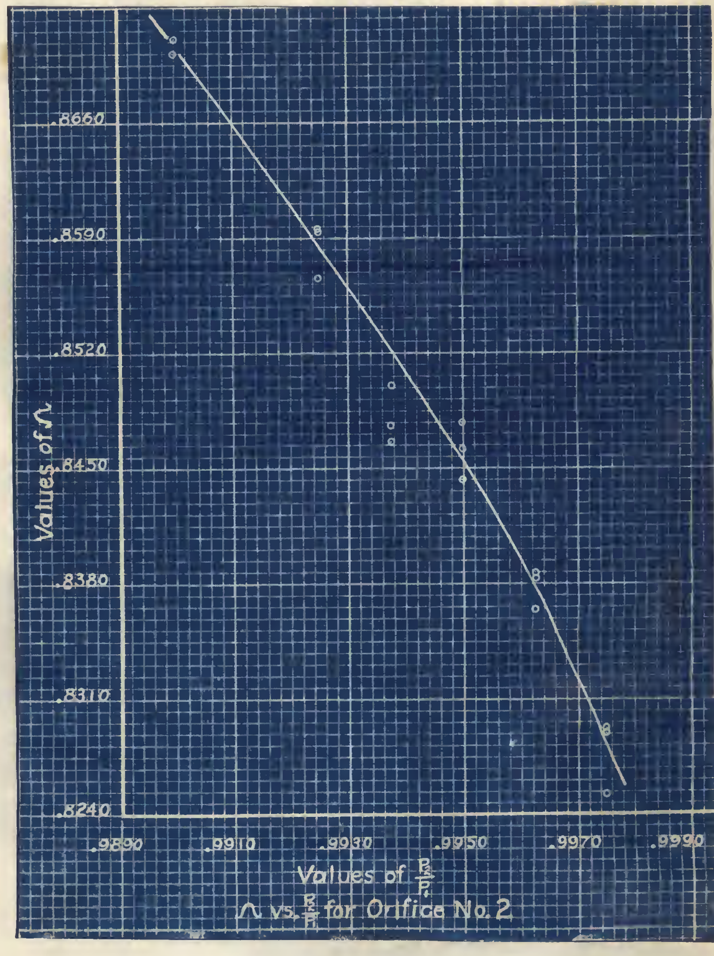

.8660
.8590
.8520
.8450
.8380
.8310
.8240
Values of ∩
.9890
.9910
.9930
.9950
.9970
.9990
Values of $\frac{P_2}{P_1}$
∩ vs. $\frac{P_2}{P_1}$ for Orifice No. 2

Figure 7

enough to warrant further consideration of the orifice as a meter for measuring small volumes of a flowing gas.

TABLE NO. 2

ORIFICE ACCURACY

Orifice No.	Accuracy %	Orifice No.	Accuracy %
1	99.62	3	99.87
1	99.07	3	99.74
1	99.88	3	99.76
5	99.95	2	99.36
5	99.65	2	99.51
5	99.56	2	99.47
4	99.92		
4	99.69		
4	99.79		